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Effect of composition and pouring temperature of Cu(20-24)wt.%Sn by sand casting on fluidity and mechanical properties

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ABSTRACT

The effect of tin composition and pouring temperature on the length of fluidity, microstructure, density, hardness, tensile strength and bending of Cu-Sn alloy with sand casting method has been investigated. Cu(20-24)wt.%Sn were casted in two different pouring temperatures (1000 ºC and 1100 ºC) in strip plate pattern sand mold. The sand mold has a length of 400 mm, width of 10 mm with a thickness of the mold cavity varied from 1.5 to 5 mm. The results show that the increase in composition (20-22) wt.% Sn decreases the length of fluidity while the composition (22-24) wt.% Sn length fluidity increase again. Increase of the pouring temperature and mold cavity thickness can increase the length of fluidity. Increasing tin composition and pouring temperature can increase the phase of α structure, porosity, hardness of the alloy and trigger the growth of dendrite columnar and secondary dendrite (DAS) microstructure.While the density, tensile strength and bending strength of the alloy tend to decrease. Increasing tin composition and pouring temperature in Cu(20-24) wt.% Sn caused the alloy to be more brittle.

Keywords: Cu-Sn; sand casting; fluidity; tin composition; pouring temperature.

INTRODUCTION

Casting is one of the oldest metal forming technique [1]. Metal casting is chosen because it has several advantages such as suitable for all types of metals, unlimited in size and shape as well as suitable for mass productions. Metal components such as bearings, pump impellers, valves and weapons components are produced with tin bronze material using metal casting. Tin bronze has been used to produce church bells since the 11th century [2,3,4], musical instruments since the 17th century [5], as well as the main materials for gamelan and gong instruments [6, 7].

Sand casting is still the best choice for metal casting. Sand casting has several advantages such as easy to work, simple equipment and high productivity [8]. However, the disadvantages of sand casting tend to produce air bubbles from the burning water as a binder and air that was trapped in the mold. Sand molds are prone to entrap air since they were using water as a binder [9]. These have been caused the rough surfaces in the casting product and the formation of porosity.

The tin bronze alloys 10-22wt%Sn are the best composition. They have high tensile strength without stretching in properties [10].The addition of Sn composition to copper was intended to improve castability, to decrease melting point, to improve corrosion resistance and decorative properties. The Cu-Sn binary phase diagram shows that the addition of Sn composition will extend solidification time of the liquid phase. The α + L phase in the hypoperitectic region is in the composition of 13.5-22wt.%Sn and the β + L phase in the hyperperitectic composition of 22-25wt.%Sn. The initial solidification of peritectic phase occurs at 798 ºC in temperature.

One of the important parameters for the succeed of metal casting is fluidity of liquid metal. The liquid metals with poor fluidity will be difficult to fill the mold cavity and causes cast defects [11, 12]. The fluidity is ability of a molten metal to flow and fill every part of the mold [13]. The fluidity length was measured from the pour point to the solidity point which was the maximum distance the liquid metal flows in the mold [14]. The fluidity was influenced by several parameters such as alloy composition, pouring temperature, viscosity, flow rate and surface tension on the mold [15]. The thin-walled mold has a poor fluidity. Solidification rate on the thin-walled mold is faster than the thick wall. Many factors that affecting the solidification rate are wall thickness, back pressure and presence of junctions [12]. The number of junctions and back pressure magnitude caused the metal ability to fill the mold decrease. The molds with complex shapes, large volumes and thin mold cavities have a higher potential in casting defects. The casting defects was found in Javanese gamelan musical instruments with 4 mm wall thickness as shown in Figure 1.

Figure 1. Defects in cast products.

The addition of the alloying composition up to the optimum limit can increase the viscosity of the molten metal which has been caused by increasing the surface tension of molten. The increasing viscosity of Cu-Sn alloys occurs in the 20-30wt.%Sn composition in the β and γ inter-metallic phases [16]. The increasing pouring temperature can be able to increase the fluidity of alloys of Cu-Sn and other metal alloys significantly in all mold types [17, 18]. The additional of Sn composition can trigger the formation of a columnar dendrite microstructure. The high temperature gradient between the liquid metal and the mold wall has increased the solidification rate. The rapid solidification rate has caused the decreasing phase of α and increasing the α + δ phase. The increasing of dendrite grain has caused the decreasing of the tensile strength and the increasing the hardness of Cu(20-24)wt.% Sn [19].

The high pouring temperatures can reduce the volume of cast metal and air binding is characterized by the formation of air bubbles. The increasing of pour temperature can cause overheat in liquid metals which tend to decrease of bell products density [4]. Research on tin bronze material related to changes in composition and pouring temperature is very important especially investigation with the aim of reducing the number of damaged products. The fluidity testing on alloy materials is very important to support success in metal casting. These study aims are to investigate the effect of adding tin composition and pouring temperature on the length of fluidity, microstructure, density, porosity, hardness, tensile strength and bending of Cu-Sn alloys with the sand casting method.

METHODS AND MATERIALS

The alloys used in this study were tin bronze Cu-20wt.%Sn, Cu-22wt.%Sn and Cu-24wt.%Sn. The Cu-Sn alloys were prepared with melted Sn(99,9%) and Cu(99,9%). The composition of Cu-Sn alloy used in the study was tested by spectrometry as shown in Table 1.

Table 1. Materials composition.

Materials	**Compositions (%)**						
	Cu	**Sn**	**Zn**	**Pb**	**Fe**	**Ni**	**Al**
20wt.%Sn	79.77	20.06	0.08	0.02	0.04	0.00	<0.001
22wt.%Sn	78.16	21.39	0.03	0.14	0.13	0.10	<0.001
24wt.%Sn	75.13	23.86	0.14	0.20	0.48	0.14	<0.001

The mold was prepared by using silica sand with a water binder. The metal pattern was coated with silica sand escaped mesh 150 in the first layer and continued with mesh 100 in the next layer. Room temperature was assumed to be 32 ºC before casting. The pouring distance is 10 mm above the pouring gate with a pouring rate of 0.004 $kg.s^{-1}$. The pouring rate was fixed. The test pattern has a dimension of 400 mm in length, 10 mm in width and a variation cavities of 1.5, 2, 3, 4 and 5 mm. The shape and dimensions of the pattern for the fluidity test were shown in Figure 2.

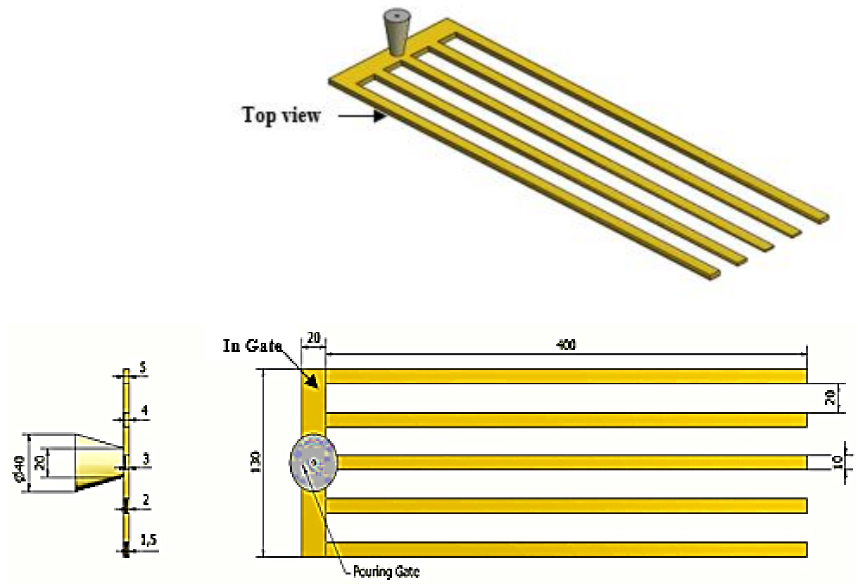


Figure 2. Pattern design (unit: mm).

The pouring temperatures were varied 1000 °C and 1100 °C. The length of fluidity was measured from in gate to the end of the cast sample (mm). Microstructural observations were performed using an optical microscope with 100X magnification. The tin bronze specimen was etched using a mixed solution between HNO_3 and H_2O. Tensile strength was tested using the ASTM E-8 and ASTM E-290 for bending test. Tensile strength specimen ASTM E-8 as shown in Figure 3. Hardness was tested using a VHN scale with a load of 100 grams, while density was calculated using Equation. (1) and porosity using Equation. (2).

$$\rho_b = \frac{w_{air}}{w_{air} - w_{water}} x\ \rho_{water} \tag{1}$$

$$\text{Porosity (\%)} = (1 - \frac{\rho_b}{\rho_{theory}})\ \text{x}\ 100\% \tag{2}$$

where, ρ_b is the actual density (g.cm^{-3}), w_{air} is the air mass (g), w_{wate} is the water mass (g), ρ_{water} is the water density (1 g.cm^{-3}), ρ_{theory} is the theoretical density of high tin bronze (8.900 g.cm^{-3}).

The stages of the casting process from preparing the mold to the casting product were shown in Figure 4. The casting process includes the placement of a metal pattern in the mold (a), the mold is filled with sand (b), the cast metal is poured into the sand mold (c) and the results of the cast product (d).

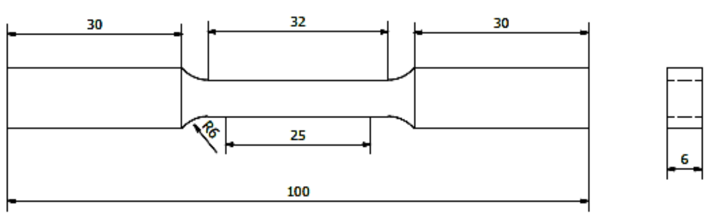


Figure 3. Tensile strength specimen ASTM E-8.

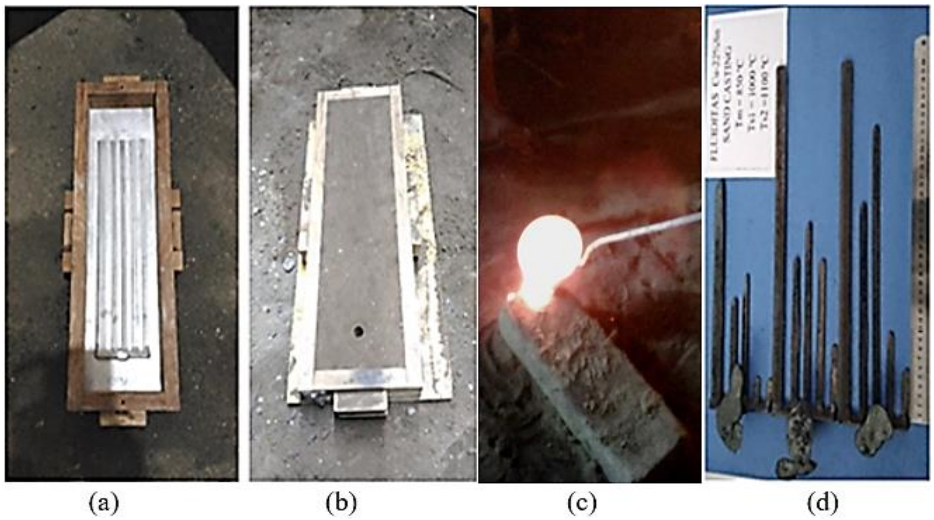


Figure 4. Fluidity test (a) pattern (b) sand mold (c) metal liquid pouring (d) cast product.

RESULTS AND DISCUSSION

Figure 5 shows the fluidity length of Cu (20-24)wt.%Sn at pouring temperature 1000 ^{o}C. The addition of tin up to 20-22wt.% tends to decrease the fluidity length. The composition of tin 24wt.% Sn shows an increasing in the length of fluidity. The composition of tin 23wt.% Sn is the solubility limit between the phases α + L and the phase β + L. The binary phase diagram of Cu-Sn shows that 13.5 - 22 wt.% Sn is in the hypoeutectic phase and 22 - 25wt.% is in hyperuetectic phase. The additional of tin composition increases viscosity and decreases the flowability and fillability. A maximum viscosity occurs at composition of 22wt.%Sn.

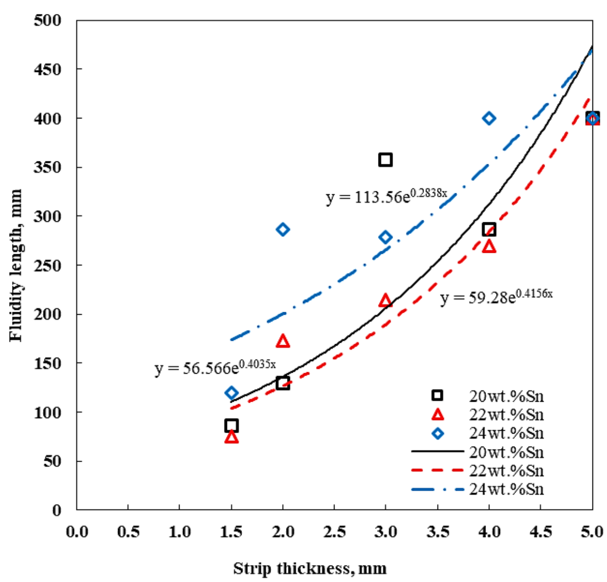


Figure 5. Fluidity length at pouring temperatur 1000 ^{o}C.

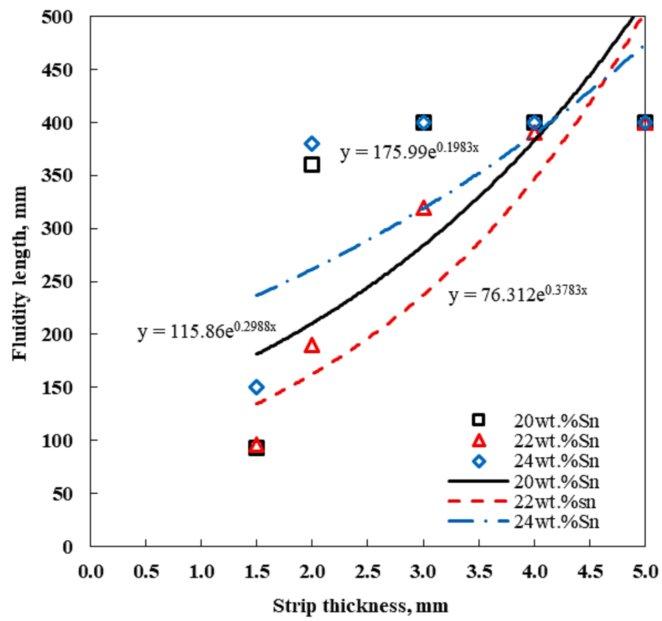
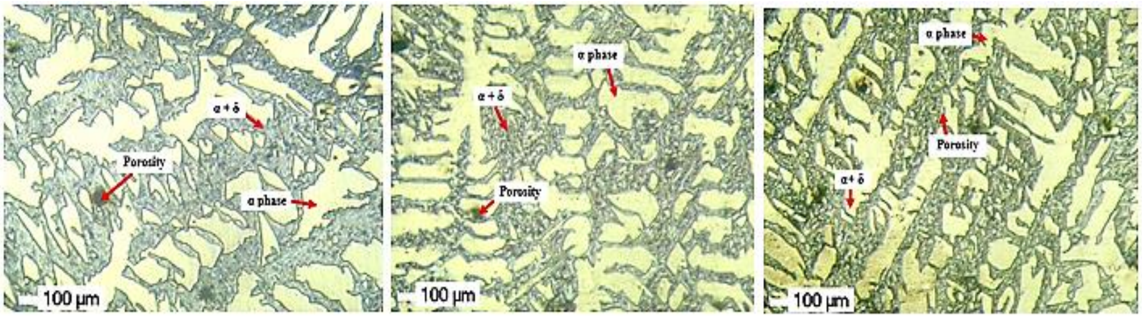


Figure 6. Fluidity length at pouring temperatur 1100 °C.

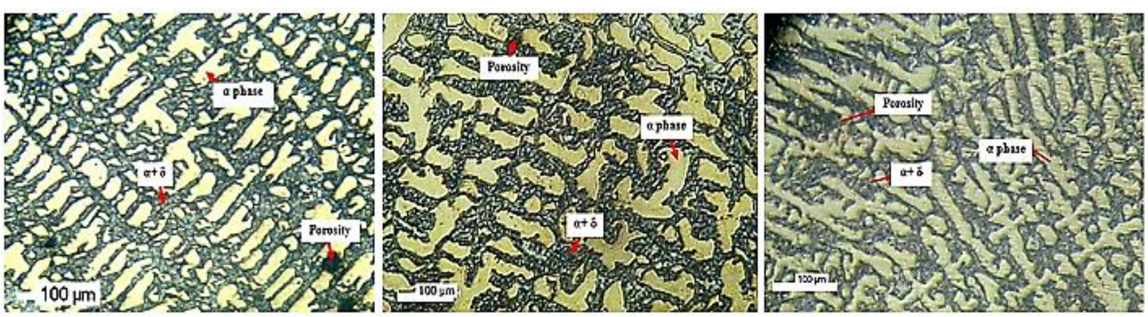
Figure 6 shows the fluidity length of Cu (20-24)wt.%Sn at pouring temperature 1100 °C. The increasing in pouring temperatures and the cavity thickness can increase the fluidity length [20]. The solidification process occurs faster in the mold cavity with a thickness between 1-2.5 mm in the sand mold [12]. The factors that affect of the solidification speed were the thickness of the mold cavity, backpressure and presence of junction. The increasing in thickness of the mold cavity can reduce back pressure so that the metal flow capability increases. The high number of junctions can increase back pressure and reduce filling capacity. Increasing in pouring temperature extends solidification time from the liquid phase to solid phase. Low pouring temperature increases the viscosity of the metal fluid which makes the fluid difficult to flow and fill the mold cavity. The increasing of pouring temperature and cavity thickness increase the fluidity length in all Cu-Sn alloys. The increasing pouring temperature can decrease viscosity and increase solidification time [21]. The longer solidification time will give the opportunity for liquid metal to flow longer. The fluidity length of liquid metal to fill the thin-walled mold cavity was very small compared with thick cavity [22]. The length of fluidity increases at superheated temperature because the distance between the liquid point and solid point was longer.



(a) (b) (c)

Figure 7. Microstructure at pouring temperature 1000 °C (a) 20wt.% Sn (b) 22wt.%Sn (c) 24wt.%Sn.

Figure 7 shows the microstructure of Cu-Sn alloys with various of tin composition at the temperature of 1000 °C (a) 20wt.%Sn, (b) 22wt.%Sn and (c) 24wt.%Sn. The additional of tin composition increases the size of the dendrite and decreases the α + δ eutectic phase precipitation. Sand molds usually use water as a binder. Low mold temperature and high pouring temperature cause higher temperature gradient. High temperature gradients increase the cooling rate and tend to form fine dendrites microstructure. The growth of columnar dendrite microstructure is in line with cast metal flow.The cooling speed of cast metal can affect the shape of the microstructure produced. The grain structure of dendrite was easily formed and enlarged by slow cooling rate. Low cooling rates increase the formation of dendrite and secondary dendrite arm spacing (SDAS). The increase in cooling rate will decreases the grain size of α, while the eutectic phase increase [23]. Increasing of tin composition and pouring temperature increase the formation of dendrite structures. The microstructures of alloys at pouring temperature of 1100 °C (a) 20wt.%Sn, (b) 22wt.%Sn and (c) 24wt.%Sn are shown in Figure 8. Increasing of pouring temperature from 1000 ºC to 1100 ºC decreases the α + δ eutectic phase precipitation.

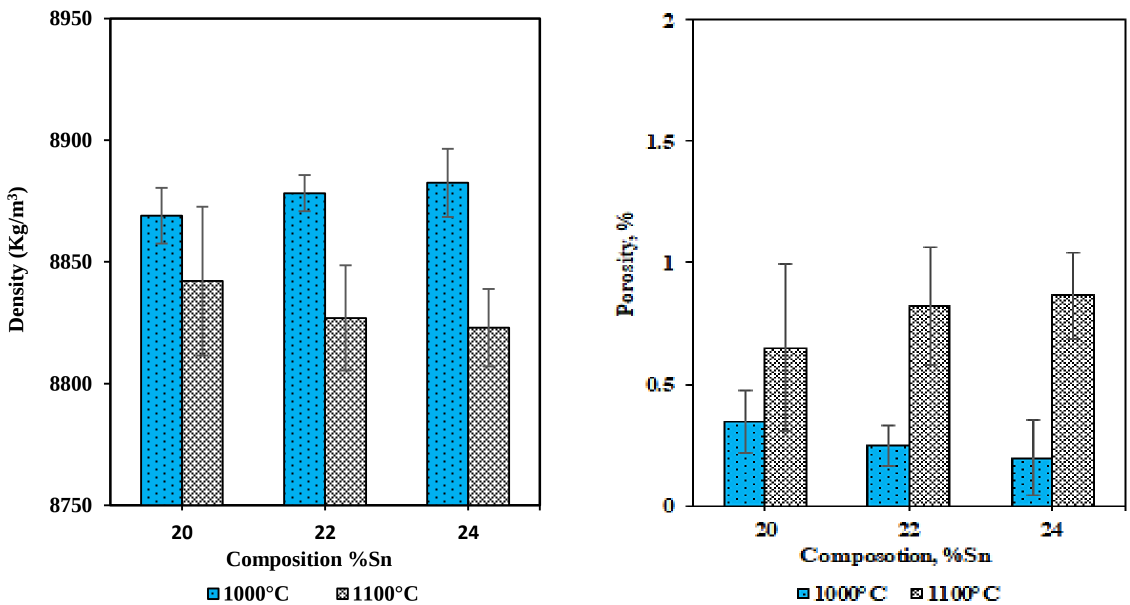


(a) (b) (c)

Figure 8. Microstructure at pouring temperature 1100 °C (a) 20wt.% Sn (b) 22wt.% Sn (c) 24wt.% Sn.

The fluidity length is also influenced by the amount of surface tension between the metal liquid and the surface of the mold wall. Sand molds that have a rough surface wall can reduce the flow of liquid metal. The large surface tension causes the length of fluidity to be shorter. The rough surface wall in the sand mold has the potential to cause a vortex flow which can cause erosion of the mold wall [24].

The additional of tin composition of 20-24wt.% Sn has not significantly affected to the Cu-Sn alloy density while an increasing of pouring temperature can reduce its density. The density on pouring temperature of 1000 °C shows the value between 8868.97 to 8882.44 kg.m^{-3} and pouring temperature of 1100 °C shows the value between 8842.13 to 8822.98 kg.m^{-3}. The various in Cu-Sn alloy density shows relatively not homogeneous due to the formation of porosity on cast objects. The decrease in density indicates increased porosity for pouring temperatur 1100 °C was shown in Figure 9(a) and 9(b). However, different results are shown at temperatures of 1000 ^{o}C. High pouring temperatures cause liquid metal to react with the environment. High pouring temperature increase porosity.The porosity was calculated using Equation. (2).



(a) (b)

Figure 9. Physical properties Cu-Sn at pouring temperature 1000 °C and 1100 °C (a) density (b) porosity

The addition of tin composition at a temperature of 1000 °C increases the density, while at a temperature of 1100 °C the density tends to decrease. The increase in density was influenced by the increase of phase α at 1000°C as shown in Figure 7. The addition of tin composition at 1100 °C temperature decreases the density by decreasing the phase α as shown in Figure 8. The porosity at 1100 °C pouring temperature increases with the addition of tin composition.

Porosity in cast objects is difficult to avoid but can be reduced by design optimization of gating and feeding system [25]. High pouring temperature and turbulent flow into the mold increase the amount of hydrogen bonded to the liquid metal can cause the formation of porosity. Figure 7 and Figure 8 show the presence of porosity in the microstructure. The large size cast products has more porosity compared to small cast products [18]. Porosity also occurs due to the decay of H_2O used as a binder between sand mold particles.

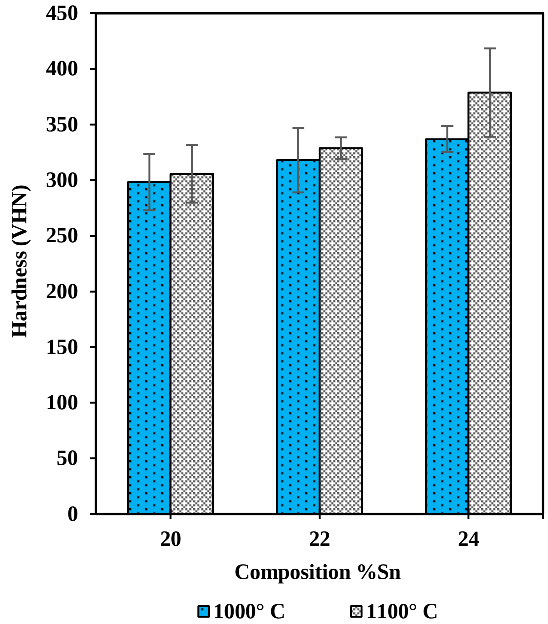
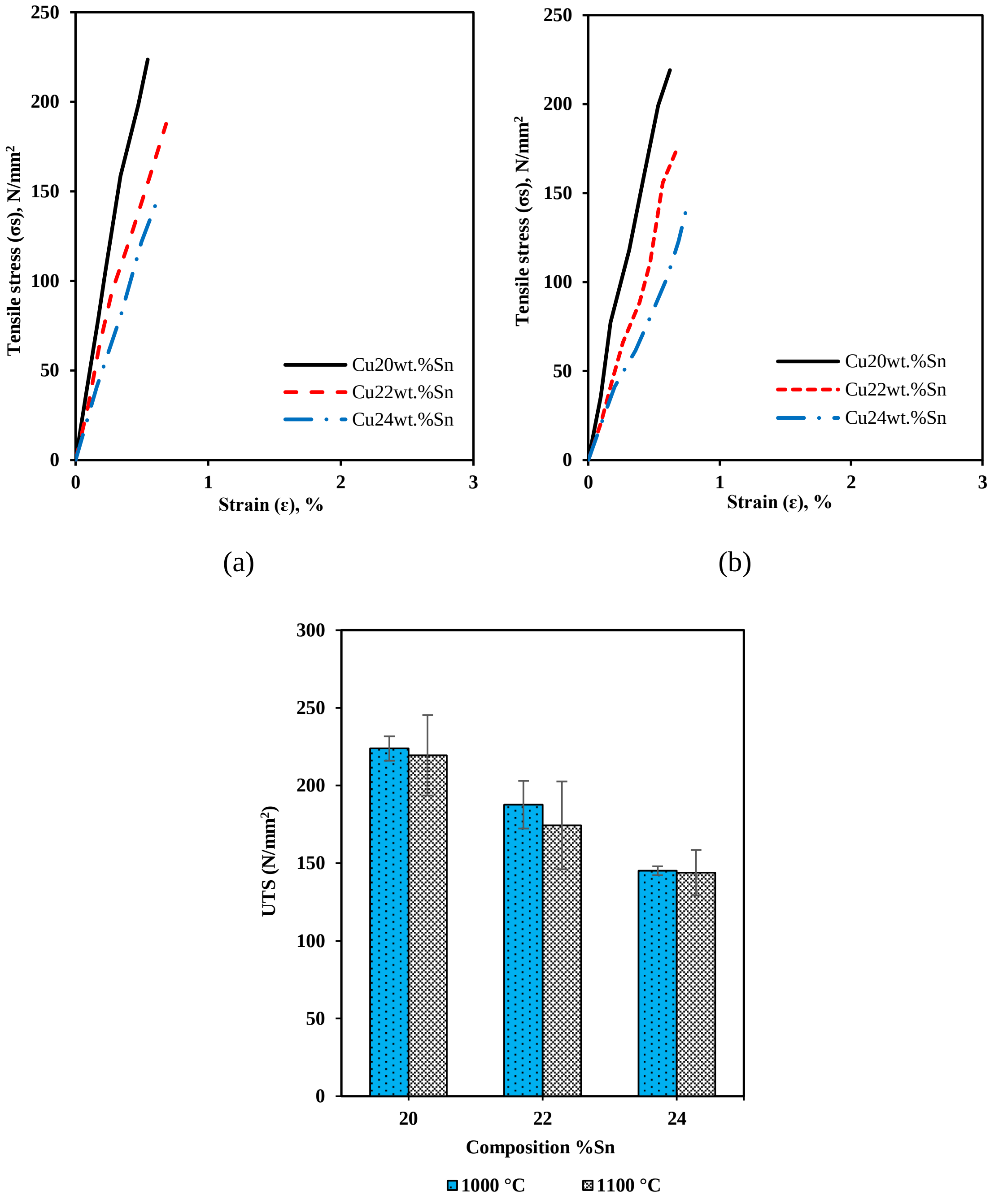


Figure 10. Hardness Cu-Sn at pouring temperature 1000 °C and 1100 °C.

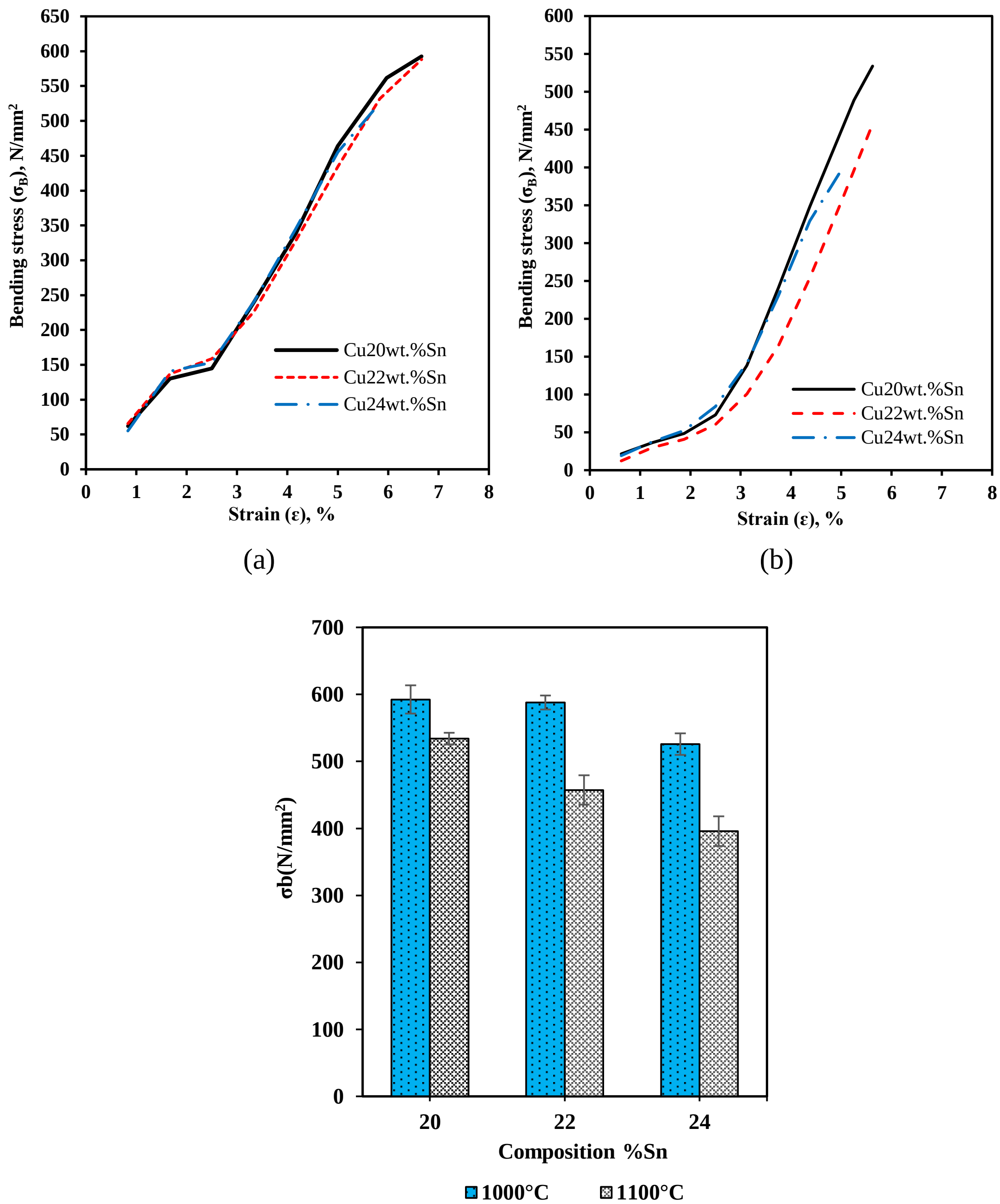
Investigations on the mechanical properties of the Cu-Sn alloys include testing of hardness, tensile strength and bending. The hardness of the Cu-Sn alloys increases with the increase of tin compositions and pouring temperatures as shown in Figure 10. The hardness was very influenced by the microstructure formed. Microstructures with small grain size and fine dendrite structure will increase the hardness of the alloy [26]. The alloy of Cu-Sn at a pouring temperature of 1100 ºC shows a dendrite structure that was finer than a pouring temperature of 1000 ºC. This phenomenon occurs in sand molds which have a relatively rapid cooling rate. The hardness of Cu-Sn alloys increases with the addition of tin composition at a temperature of 1000 °C. At a temperature of 1000 °C microporosity was formed less in percentage as shown in Figure 9(b).

The tensile strength and the bending strength of Cu-Sn alloys decrease with the increasing of Sn compositions and pouring temperatures. The tensile strength curve Cu-Sn at pouring temperature 1000 ºC shown Figure 11(a), pouring temperature 1100 ºC shown Figure 11(b) and tensile strength Cu-Sn as shown in Figure 11(c). The bending strength curve at pouring temperature 1000 ºC are shown Figure 12(a), pouring temperature 1100 ºC shown Figure 12(b) and bending strength Cu-Sn as shown in Figure 12(c). The addition of tin composition significantly reduces tensile strength, however the increase in pouring temperature does not significantly increase the tensile strength. The additional of tin composition does not affect the bending strength, however the increasing in pouring temperature decreases the bending strength significantly. The pouring temperature was the main factor that influences the value of tensile strength and elongation on metal casting [27].



(c)

Figure 11. Mechanical properties Cu(20-24)wt.%Sn
(a) tensile strength T=1000 °C (b) tensile strength T=1100 °C (c) tensile strength/UTS.



(a) (b) (c)

Figure 12. Mechanical properties Cu(20-24)wt.%Sn
(a) bending strength T=1000 °C (b) bending strength T=1100 °C (c) bending strength.

Addition of tin composition and increase in pouring temperature increase the formation of the eutectoid α + δ phase. The decrease in tensile strength and bending strength is caused to the increase in the size of the dendrite microstructure as shown in Figure 6 and Figure 7. Increasing the pouring temperature decreases the solidification rate from the liquidus point to the solidus point on the Cu-Sn phase diagram. Slow solidification rate increases the size of dendrite microstructure. The additional of tin composition up to the limit of <22wt.%Sn shows the structure of FCC (α) causes the alloy tend to be ductile, while in composition >22wt.%Sn shows the relatively brittle BCC (β) structure. The results of the mechanical cu-sn alloy test are shown in Table 2.

Table 2. Density and mechanical properties tin bronze Cu-Sn .

	Pouring temperature 1000 ºC				**Pouring temperature 1100 ºC**			
wt. %Sn	**Density kg/m^3**	**VHN**	**UTS (N/mm^2)**	**σb (N/mm^2)**	**Density kg/m^3**	**VHN**	**UTS (N/mm^2)**	**σb (N/mm^2)**
20	8868.97	298.16	223.84	592.53	8842.13	305.77	223.64	533.95
22	8878.20	317.95	187.74	588.03	8826.98	328.83	174.44	457.39
24	8882.44	336.87	145.13	525.84	8822.98	378.73	149.22	395.94

CONCLUSIONS

The addition of tin composition at 20-22wt.%Sn reduces the length of fluidity while adding a composition of 24wt.% Sn length fluidity increases again. An increasing in pouring temperature and thickness of the mold cavity can increase the length of fluidity. The increasing of tin composition and pouring temperatures increase the size of dendrites in the alloy microstructure and decreases the α + δ eutectoid phase precipitation. The density of Cu(20-24)wt.%Sn tends to decrease due to an increasing in pouring temperature and the amount of porosity formed. Increased pouring temperature and tin composition can reduce tensile and bending strength while hardness of alloys increases but is brittle.

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